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On The Evolution of X-ray Clusters at High Redshift[1]

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ABSTRACT

We report on the first results from a redshift survey of a flux-limited sample of X-ray clusters selected serendipitously from the ROSAT PSPC data archive. We spectroscopically confirm 15 clusters in the range $0.3 < z < 0.7$, to a flux limit of $\simeq 3.9 \times 10^{-14}\,\mathrm{erg\,s^{-1}\,cm^{-2}}$, over a survey area of 17.2 deg^2. The surface density of clusters in our survey is $2.0^{+0.4}_{-0.3}\,\mathrm{deg}^{-2}$, in good agreement with the number density of cluster candidates detected using algorithms designed to search for very extended sources. The number of clusters detected between $0.3 < z < 0.7$ is consistent with a prediction based on a simple extrapolation of the local X-ray cluster luminosity

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function, which indicates that over this redshift range no significant evolution in the cluster population has taken place. These results are in conflict with recent claims that the number density of X-ray clusters found in deep ROSAT PSPC pointings evolves rapidly beyond $z = 0.3$.

Subject headings: galaxies: clusters: general — galaxies: evolution — X-rays: galaxies — X-rays: general

1. Introduction

Galaxy clusters are the largest gravitationally bound structures in the universe and can be observed out to high redshift, providing a rich source of information on the history of structure formation. The form of cluster evolution with look-back time is a very sensitive probe of hierarchical structure formation models. Assuming a CDM-like power spectrum and a self-similar model for structure evolution, Kaiser (1986) predicted that the comoving number density of clusters should increase with redshift, i.e. positive evolution. More sophisticated analytic and N-body models, which include gravitational instability theory and hydrodynamics, predict a decrease in the number density of clusters with redshift (negative evolution) for only the very brightest clusters (X-ray luminosities, $L_x \gtrsim 5 \times 10^{44}\,\mathrm{erg\,s^{-1}}$), with little evolution at lower luminosities (e.g. Kaiser 1991; Cen & Ostriker 1994).

Until recently the only available distant cluster catalogues were optically selected, showing little evidence for evolution in the cluster space density out to $z \simeq 0.5$ (e.g. Gunn, Hoessel & Oke 1986; Postman et al. 1996). However, one of the most intriguing results to emerge in recent years is the lack of high redshift X-ray luminous clusters in the Einstein Extended Medium Sensitivity Survey (EMSS, Gioia et al. 1990; Henry et al. 1992) and other X-ray surveys (Edge et al. 1990). These studies concluded that there has been significant negative evolution over short look-back times in the bright end of the cluster X-ray luminosity function (XLF). The evolution found by Edge et al. (1990) is likely to be the result of unfortunate sampling in the redshift range $0.1 < z < 0.15$ (Ebeling et al. 1995), while the evidence for negative evolution reported by Henry et al. (1992) is critically examined by Nichol et al. (1997) using ROSAT pointed observations of EMSS clusters.

We are now able to test the negative evolution scenario using the publicly available data archive of the ROSAT Position Sensitive Proportional Counter (PSPC). The greater spatial resolution and sensitivity, combined with the lower background, of the ROSAT PSPC compared to the EINSTEIN IPC means that cluster samples can be compiled to a flux limit an order of magnitude fainter than that of the EMSS. We have carried out a survey for serendipitously detected X-ray clusters from the PSPC data archive in order to study the cluster population at high redshift (Burke et al. 1996). This project is referred to as the Serendipitous High-redshift

Archival ROSAT Cluster survey (SHARC), although our selection technique is completely different to that described in Nichol et al. (1997), who use a source detection algorithm based on a wavelet transform to re-examine the EMSS cluster sample. There are several groups currently using the PSPC database to compile distant cluster surveys (RIXOS, Castander et al. 1995; RDCS, Rosati et al. 1995; WARPS, Scharf et al. 1996). The purpose of this letter is to report on the number of spectroscopically confirmed high redshift clusters in our survey and to compare our results with those of other groups. In particular we make a direct comparison with RIXOS, who have claimed that the dearth of high redshift clusters in their sample strengthens the claims of negative evolution (Castander et al. 1995). In this letter we use $H_0 = 50\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ and $q_0 = 0.5$.

2. The Cluster Sample

The ROSAT PSPC provides wide field imaging capabilities with moderate spatial and spectral resolution (Trümper 1983). On axis the PSPC has a PSF with a FWHM of 25″ at 1 keV and an energy resolution $\Delta E/E \simeq 0.4$ over the range $0.1 - 2.4$ keV. Although the instrument has a 1° radius field of view, the off axis PSF degradation and the vignetting caused by the window support structure generally limit analysis to within a radius of 18′. The X-ray emission from rich clusters of galaxies is spatially extended, with a surface brightness profile well fit by a King profile:

$$S_x(r) \propto (1 + (r/r_c)^2)^{1/2-3\beta}, \tag{1}$$

with a core radius (r_c) of $200 - 500$ kpc and $\beta \simeq 2/3$ (Jones & Forman 1984). Assuming no evolution in r_c and β, clusters can be resolved out to $z \simeq 1.0$ by the PSPC. Ideally we would like to optically identify all the X-ray sources in our survey, regardless of extent. However, AGN are the primary X-ray source population at flux limits of $10^{-13} - 10^{-14}\,\mathrm{erg\,s^{-1}\,cm^{-2}}$ (Georgantopoulos et al. 1996), outnumbering clusters by 10 to 1. Since X-ray emission from AGN is unresolved by the PSPC, we can significantly reduce the contamination these sources introduce into our survey by restricting our attention to extended sources only. Clusters have typical ICM temperatures of 2 – 10 keV (David et al. 1993), so we can reduce the contamination from soft sources and Galactic emission by restricting our analysis to the $0.5 - 2.0$ keV pass band.

Our survey consists of 66 deep ROSAT pointings which satisfy the following criteria: exposure times greater than 10 ks, $|b| > 20°$ and $\delta < 20°$. The Galactic neutral hydrogen column density for these fields varies between 2 and $7 \times 10^{20}\,\mathrm{cm^{-2}}$ which, together with the average exposure time of 18 ks, results in an average flux limit $\simeq 3.9 \times 10^{-14}\,\mathrm{erg\,s^{-1}\,cm^{-2}}$. Due to the degradation of both the PSF and the detector effective area with off-axis position, we limit our survey to the central 18′ of each field, which results in a total survey area of $\simeq 17.2$ deg^2, after masking out the original targets of the observations. Briefly, the analysis begins with screening out data taken during periods of high aspect error or particle background. We compute a global estimate of the background and use a sliding box technique, with a detect cell size of 30″, coupled with the Cash statistic (Cash 1979) to search for sources. These sources are tested for extent by comparing the

photon distribution to the PSF, modelling both the positional and spectral dependence of the PSF. Those sources which show significant ($\geq 3\sigma$) angular extent are flagged as cluster candidates. The degree of completeness in our survey depends heavily on the extent of the cluster X-ray emission and the sensitivity of the extended source algorithm (e.g. see Scharf et al. 1996). Our detection method is designed to pick-up moderately extended sources of size $\leq 1'$ which is a good match to the expected angular size of clusters in the range $0.3 < z < 1$. At this stage we do not know to what extent our completeness is compromised by ignoring intrinsically unresolved sources. However, both the surveys of Georgantopoulos et al. (1996) and RIXOS, which have optically identified all point sources in deep ROSAT PSPC fields, detect very few clusters with point-like X-ray emission (Georgantopoulos et al. 1996; Castander 1996a, private communication). In addition, we are in the process of carrying out simulations to estimate the completeness and the sensitivity of our selection method to sources of different fluxes with sizes ranging from point-like to very extended ($\geq 1'$).

We have carried out an optical identification programme of the extended sources, obtaining both imaging and multi-object spectroscopy using the European Southern Observatory 3.6m and the Anglo-Australian 3.9m telescopes. Typically we have redshifts for $5 - 10$ galaxies per cluster. Our final sample consists of clusters which satisfy the joint criteria of both extended X-ray emission and multiple redshifts, which ensures minimal contamination from AGN. Full details of the survey, including the cluster identification procedure, redshift reduction and an estimate of the survey completeness from simulations will be given in a forthcoming paper (Burke et al., in preparation). As a result of the optical observations we have identified 35 clusters ranging from nearby poor clusters to high redshift rich clusters. Figure 1 shows our four most distant clusters with X-ray contours overlaid on CCD R band images.

3. Comparison with other ROSAT Surveys

We have spectroscopically confirmed a total of 35 clusters over an area of 17.2 deg^2, giving a cluster surface density of $2.0^{+0.4}_{-0.3}\,\mathrm{deg}^{-2}$ ($1\,\sigma$ Poisson errors taken from Gehrels 1986). Two surveys designed to detect very extended sources in ROSAT PSPC pointings have recently published surface densities of extended sources found in the $0.5 - 2.0\,\mathrm{keV}$ band: RDCS use a wavelet transform algorithm and report a surface density of $\simeq 2.5$ deg^{-2} at a flux limit of 3×10^{-14} $\mathrm{erg\,s^{-1}\,cm^{-2}}$; WARPS use a Voronoi tesselation and percolation algorithm and detect 2.1 - 3.1 deg^{-2} above an intrinsic flux limit of 4.5×10^{-14} $\mathrm{erg\,s^{-1}\,cm^{-2}}$. Although neither sample is fully identified (Rosati et al. 1995 report spectroscopic confirmation for a subset of their sample whereas Scharf et al. 1996 leave discussing their optical follow up to a future paper), their results are similar to our surface density of spectroscopically confirmed clusters.

In Table 1 we summarise our survey statistics along with those of RIXOS and show the corresponding redshift distributions in Figure 2. Despite the similarity of the surveys in terms of limiting X-ray flux and total area surveyed, it is immediately apparent that we detect many more

high redshift clusters than RIXOS; beyond $z = 0.3$ we find 15 clusters compared to their 4. Using Poisson statistics, the probability that this difference could arise by chance is 2.1×10^{-4} and is therefore ruled out at a significance of $3.5\,\sigma$. The lack of high redshift clusters in the RIXOS sample could be due to their detection method, as suggested by Scharf et al. 1996, or due to optical misclassification.

4. Evidence For Evolution

We examine the redshift histogram in Figure 2 for evidence of evolution by predicting the expected number of clusters in the interval $0.2 < z < 0.7$ using the low redshift cluster XLF of De Grandi (1996). For clusters at lower redshifts, the results become unreliable due to the small volume sampled and the uncertainties in the XLF at low luminosities. A similar calculation was carried out by Castander et al. (1995) for the RIXOS survey using the cluster XLF of Edge et al. (1990). The cluster XLF of De Grandi (1996) is well matched to our dataset since it is a purely X-ray selected cluster sample, identified from the ROSAT All Sky Survey. The differential XLF, $n(L)$, is modelled using a Schechter function,

$$n(L_{44}) = A \exp\left(-L_{44}/L_{*}\right) L_{44}{}^{-\alpha}, \tag{2}$$

where L_{44} is the X-ray luminosity in units of $10^{44}\,\mathrm{erg\,s^{-1}}$, $\alpha = 1.32^{+0.21}_{-0.23}$, $L_* = 2.63^{+0.87}_{-0.58}\,10^{44}\,\mathrm{erg\,s^{-1}}$ and $A = 4.29^{+0.39}_{-0.31} \times 10^{-7}\,\mathrm{Mpc^{-3}}\,(10^{44}\,\mathrm{erg\,s^{-1}})^{\,\alpha-1}$.

Using this model we can estimate the number of high redshift clusters we expect to detect by integrating equation 2 above the minimum detectable luminosity for each redshift interval. The exposure time, background count rate and a model of the off axis behaviour of the PSF (Hasinger et al. 1994) are used to predict the minimum detectable count rate at each redshift, after correcting for the flux falling outside the detection cell using equation 1, with $\beta = 2/3$ and $r_c = 250$ kpc. We use a 6 keV thermal bremsstrahlung model to convert count rates to fluxes, which are then corrected for Galactic absorption and k-corrected to the $0.5 - 2.0$ keV band. Both our survey and the EMSS have a flux limit which varies from field to field. While this complicates the analysis, the V/V_{max} method used by Henry et al. (1992) fully corrects for this effect and our procedure follows the same technique.

The results summarised in Table 1 demonstrate that in the redshift intervals $0.2 - 0.3$ and $0.3 - 0.7$, the number of X-ray clusters predicted and observed differ by only $1.3\,\sigma$ and $0.9\,\sigma$ respectively. Despite the possibility of residual incompleteness our data provides no evidence for the negative evolution reported by Castander et al. (1995).

To test whether uncertainties in the local XLF can bias this analysis, we have repeated the calculation using the cluster XLF of Ebeling et al. (1996), which is not strictly X-ray selected, but based partly on the optical catalogues of Abell and Zwicky. The XLF is modelled as before, with $\alpha = 1.78 \pm 0.09$, $L_* = (8.92 \pm 1.66)\,10^{44}\,\mathrm{erg\,s^{-1}}$ and $A = (5.72 \pm 0.95) \times 10^{-7}\,\mathrm{Mpc^{-3}}\,(10^{44}\,\mathrm{erg\,s^{-1}})^{\,\alpha-1}$,

over the energy range $0.1 - 2.4$ keV. Converting to the $0.5 - 2.0$ keV band, we predict $6.9^{+1.0}_{-1.6}$ clusters between $0.2 < z < 0.3$ and $23.1^{+4.8}_{-4.8}$ clusters between $0.3 < z < 0.7$. These results are virtually identical to those obtained above, indicating that our predictions are insensitive to potential biases in the local XLF.

One difference between our survey and RIXOS is that, in common with EMSS, our flux limit varies with the exposure time and Galactic neutral hydrogen column density of each observation, with an rms variation of $\simeq 20\%$, whereas RIXOS impose a constant flux limit of $3 \times 10^{-14}\,\mathrm{erg\,s^{-1}\,cm^{-2}}$ across all fields. Therefore one possibility is that the 'missing' clusters lie in our deepest fields, with fluxes below the RIXOS flux limit. However, if we replace the individual flux limits of each field with the average value quoted in Table 1, the predicted number of clusters remains essentially unchanged, $19.7^{+5.0}_{-3.9}$ compared with $19.4^{+4.9}_{-3.9}$. Hence the deeper fields in our survey do not unduly bias our results.

5. Conclusions

We have carried out a redshift survey of extended sources selected from the ROSAT PSPC pointed data archive over an area of 17.2 deg^2 and to a depth of $3.9 \times 10^{-14}\,\mathrm{erg\,s^{-1}\,cm^{-2}}$ in the energy range $0.5 - 2.0$ keV. Spectroscopic follow-up observations have produced a sample of distant X-ray selected galaxy clusters. The surface density of our spectroscopically confirmed cluster sample is $2.0^{+0.4}_{-0.3}\,\mathrm{deg}^{-2}$, in good agreement with the number density of cluster candidates detected using algorithms designed to search for very extended sources (RDCS and WARPS). In addition, the redshift histogram of our clusters is consistent with a simple extrapolation of the local luminosity function of X-ray clusters from De Grandi (1996). This indicates that no substantial negative evolution has taken place in the cluster population over the redshift range $0.3 < z < 0.7$.

After this manuscript was accepted we spectroscopically confirmed a further cluster at $z = 0.672$ from service observations carried out on the 4.2m WHT. This completes the identification of extended sources and brings the number of clusters in our survey which are beyond $z = 0.3$ to 16, which marginally increases the discrepancy between our sample and that of RIXOS.

This research has made use of data obtained from the Leicester Database and Archive Service at the Department of Physics and Astronomy, Leicester University, UK. We thank Sabrina De Grandi for providing us with the errors on the ESO KP cluster XLF. Mel Ulmer and Brad Holden are acknowledged for their support of the SHARC survey. CAC and DJB acknowledge PPARC for an Advanced Fellowship and Postgraduate Studentship respectively. AKR acknowledges support from NASA ADP grant NAG5-2432. We thank the staff at both the European Southern Observatory and the Anglo-Australian Observatory for use of these facilities.

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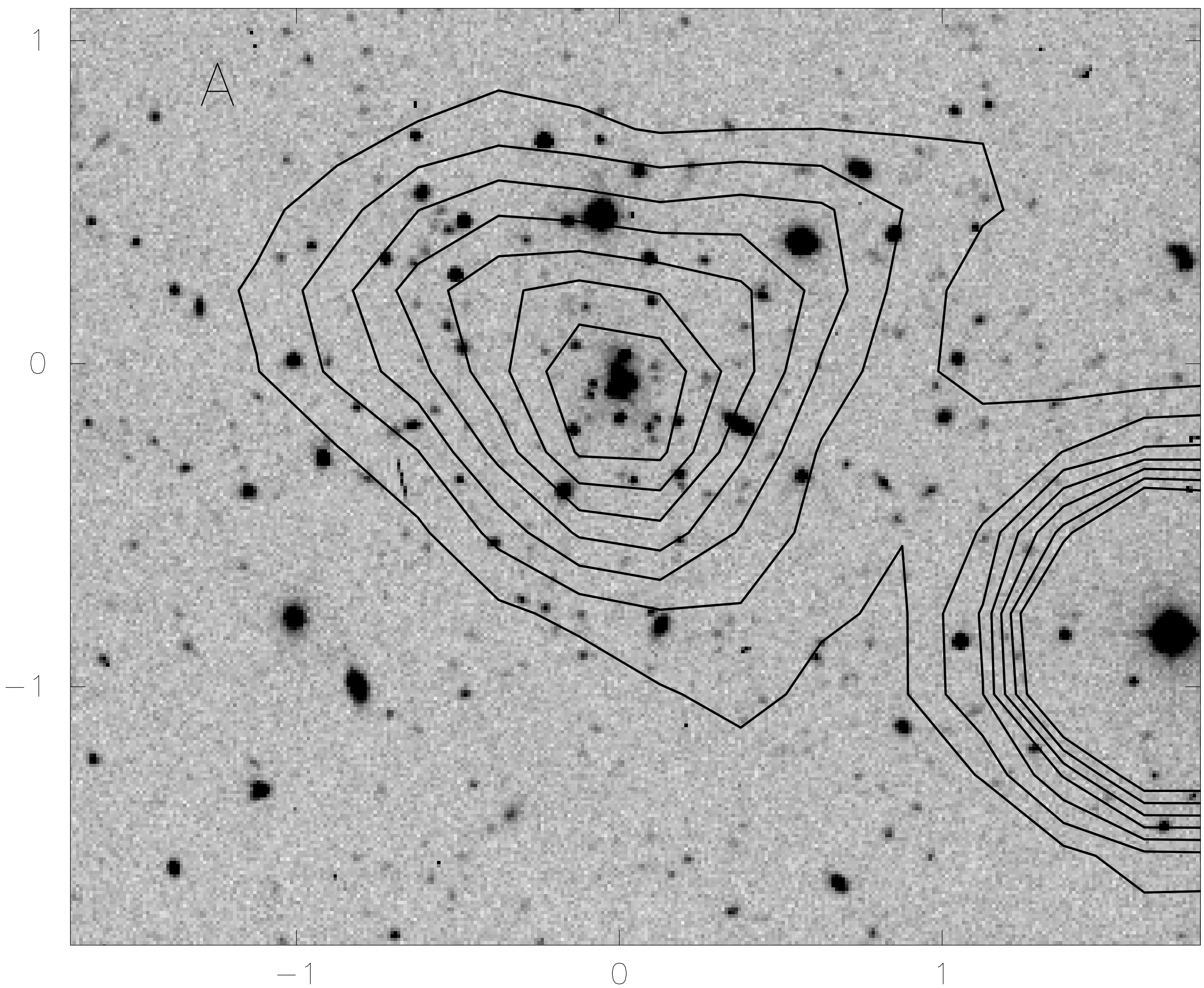
Fig. 1.— X-ray contours, for the $0.5 - 2.0\,\mathrm{keV}$ band overlaid on CCD R band exposures of our 4 most distant clusters. The images are 10 minute exposures taken at the ESO 3.6m. Axis units are in arcminutes and the X-ray images have been lightly smoothed and begin at 3σ above the background with a step size of 3σ. A is at $z = 0.576$, B at $z = 0.550$, C at $z = 0.505$ and D at $z = 0.484$. At these redshifts 1 arcminute subtends ~ 440 kpc.

Fig. 2.— Comparison of our complete cluster redshift distribution (solid line) with that of the RIXOS survey (dotted line). The RIXOS data are taken from Castander et al. (1995) for $z \geq 0.2$ and Castander (1996b) for $z < 0.2$.

Survey	Ω (deg^2)	Flux limit ($10^{-14}\,\mathrm{erg\,s^{-1}\,cm^{-2}}$)	N_c ($0.2 < z < 0.3$)	N_c ($0.3 < z < 0.7$)
This Work	17.2	3.9	$8^{+4.0}_{-2.8}$ ($4.3^{+1.6}_{-1.2}$)	$15^{+5.0}_{-3.8}$ ($19.4^{+4.9}_{-3.9}$)
RIXOS	14.9	3.0	$9^{+4.1}_{-2.9}$ (8)	$4^{+3.2}_{-1.9}$ (25)

Table 1: Comparison between this work and RIXOS for all $z > 0.2$ clusters. The errors on the number of clusters found are Poisson. The numbers in brackets for our survey are the predictions for the number of clusters observed based on a model of our selection function and the XLF of De Grandi (1996), along with the 1σ errors from the simulations. The values for RIXOS have been taken from Castander et al. (1995), which uses the XLF of Edge et al. (1990).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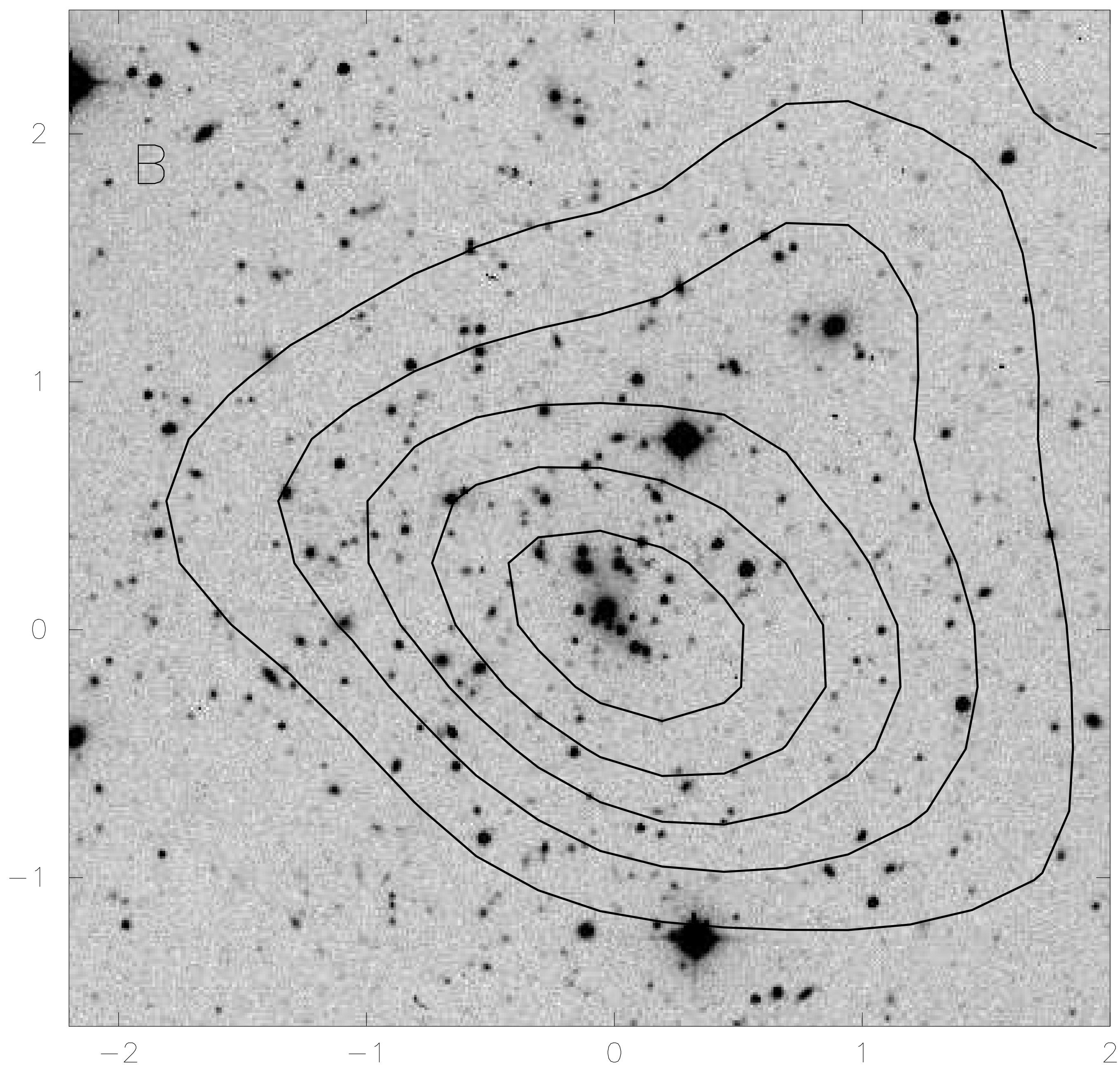
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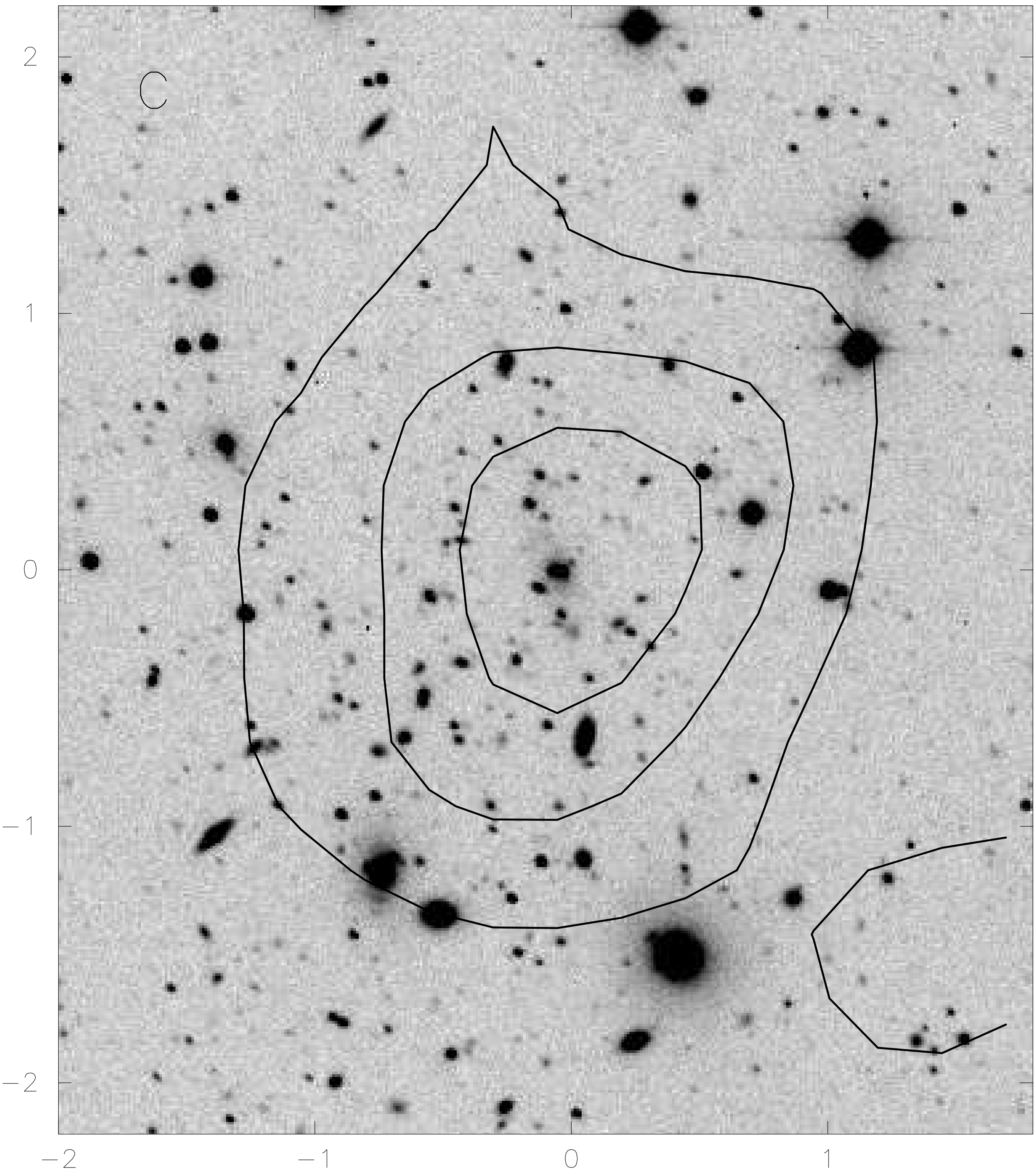
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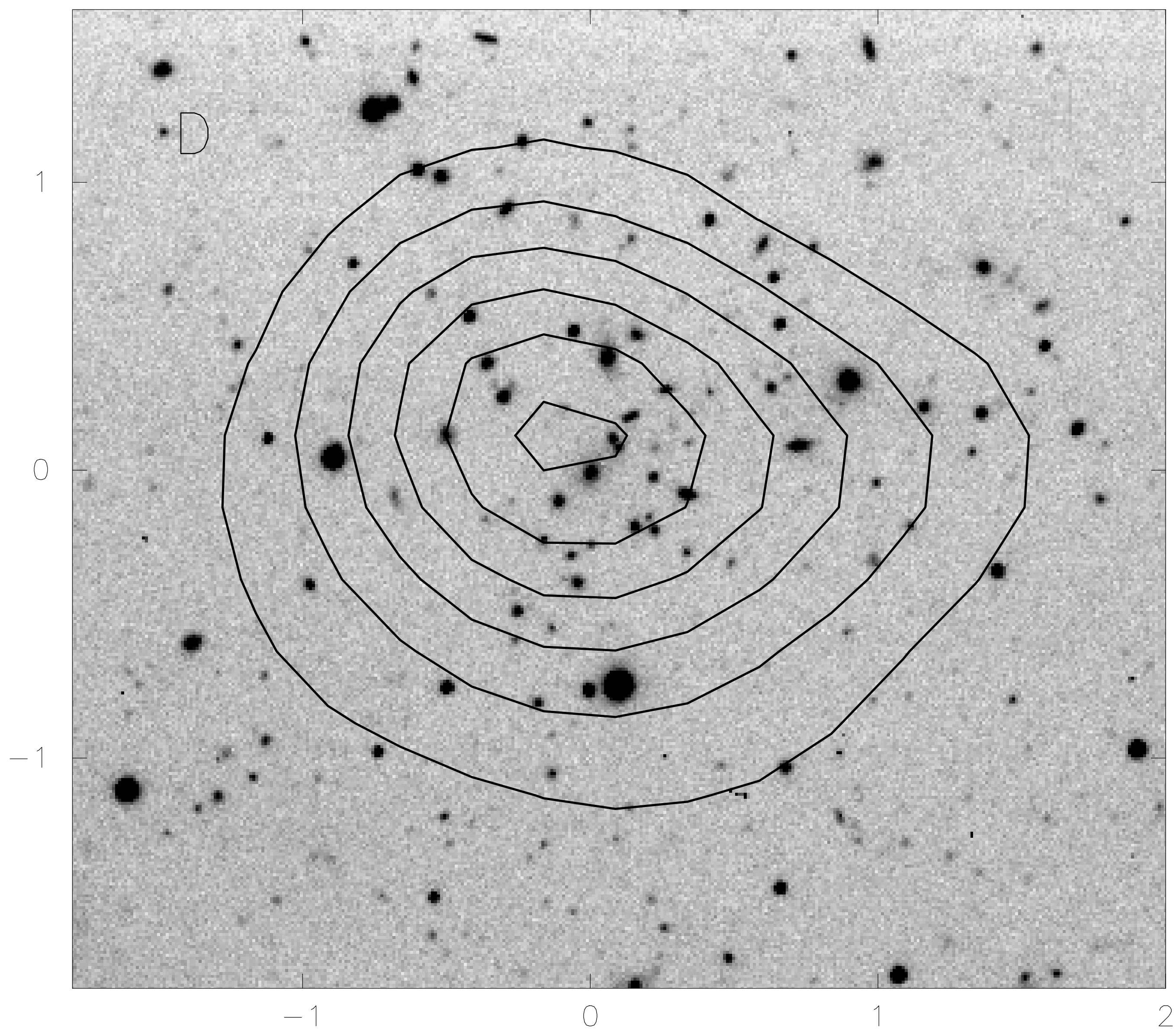
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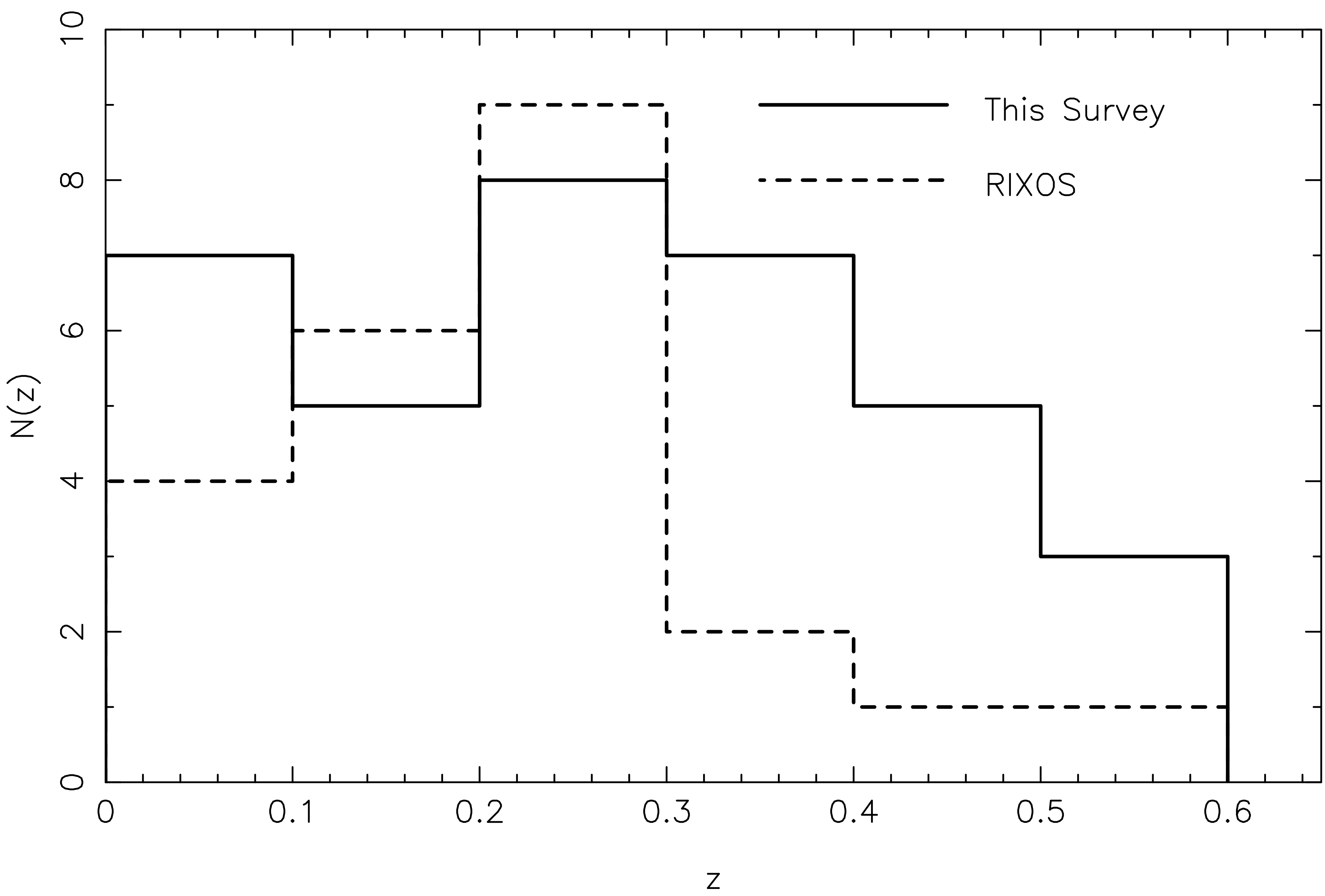

This Survey
RIXOS
N(z)
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